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# Scaling Behavior of Public Procurement Activity

António Bernardo Curado Estevão

Dissertation presented as partial requirement
for obtaining the degree

Master of Data Science and Advanced Analytics

NOVA Information Management School
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by

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[1] https://github.com/joaomlourenco/novathesis [2] http://www.di.fct.unl.pt

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To the future and the challenges that lay ahead.

# Abstract

How can we know if local governments are spending public money efficiently? Public procurement accounts for a significant share of OECD countries' expenditures. Therefore, governments are expected to execute them as efficiently as possible. Yet, there is a lack of methods that allow for an adequate comparison of procurement activity between local authorities with different scales, representing a challenge for policymakers and academics. Here, we use methods from Urban Scaling Laws literature to study public procurement activity among 278 Portuguese municipalities. We find that public expenditure scales sub-linearly with population size, indicating economies of scale for public spending as cities increase their population. The scaling behavior persists after desegregating by contract type, namely Works, Goods, and Services. Moreover, using the Scale-Adjusted Indicators, which represent the deviations from the scaling laws, we characterize different patterns of procurement activity among regional groups. Thus, we obtain a new local characterization of municipalities based on the similarity of procurement activity. These results make up a framework for quantitatively study local public expenditure by enabling policymakers a more appropriate ground for comparative analysis.

**Keywords:** Public Policy, Public Procurement, Comparative Analysis, Urban scaling laws

# Resumo

Como saber se os governos locais estão a gastar o dinheiro público de forma eficiente? A contratação pública corresponde a uma parte significativa das despesas dos países da OCDE. Espera-se que os governos a executem de forma eficiente. Ainda assim, faltam métodos que permitam uma comparação adequada da atividade de compras entre instituições, o que representa um desafio para legisladores e académicos. Aqui, são usados métodos da literatura de Leis de Escala Urbana para estudar a atividade de compras públicas entre 278 municípios portugueses. Descobrimos que a despesa pública escala sublinearmente com o tamanho da população, indicando economias de escala para gastos públicos conforme as cidades aumentam sua população. O comportamento de dimensionamento persiste após a dessegregação por tipo de contrato. Além disso, usando os indicadores ajustados à escala, que representam os desvios das leis de escala, caracterizamos diferentes padrões de atividade de compras entre os grupos regionais. Assim, obtemos uma nova caracterização local dos municípios com base na semelhança da atividade de compras. Estes resultados constituem uma estrutura para estudar quantitativamente os gastos públicos locais, permitindo aos legisladores uma base mais apropriada para análises comparativas.

**Palavras-chave:** Politicas Públicas, Contratação Pública, Análise Comparativa, Leis de Escala Urbana

# Contents

**List of Figures** xv

**List of Tables** xvii

**1 Introduction** 1

**2 Related Work** 3

**3 Materials and Methods** 9

**4 Results Discussion** 19

**5 Conclusion** 33

**Bibliography** 37

**Appendix** 47

# List of Figures


3.1 Regional divisions in Portugal . . . . . 11
3.2 Time and geographical procurement distribution . . . . . 13
3.3 Total number of contracts per CPV . . . . . 14
3.4 Procurement total expenses per CPV . . . . . 14

4.1 Scaling coefficients for socio-economic and procurement data 20
4.2 Procurement Scalling Coefficients per type and year . . . . 21
4.3 Scalling Law with Scale-Adjusted Indicators . . . . . 24
4.4 Distributions of Scale-Adjusted Indicators (SAI). . . . . 25
4.5 Ranking of Procurement Activity Portuguese Municipalities 26
4.6 Correlations between the Scale-Adjusted and Regional Indicators . . . . . 27
4.7 Yearly Differences in the Scaling-Adjusted Indicators between different groups of Portuguese Municipalities . . . . 28
4.8 Clustering of Municipalities according to the Scale-Adjusted Indicators patterns . . . . . 30

# List of Tables

3.1 Description of the type of Public Procurement Contracts according to the UE public procurement guidelines. . . . 15
3.2 Socio Economic variables description . . . . . 17

CHAPTER 1

# INTRODUCTION

Public procurement is defined by the Organisation for Economic Co-operation and Development (OECD) as the purchase by governments and state-owned enterprises of goods and services [1]. Currently it stands as an essential public sector instrument empowering policymakers to effectively push-forward inclusive, [2] innovation driven, and economic growth generating [3–5] policies. Among OECD countries, public procurement weighs, on average, 29% of all governmental expenditures [2] and 12% of global OECD country's gross domestic product (GDP) (14%[6] among European Union (EU) countries). Moreover, given the relevance for economic activity of public procurement mechanisms, the European Commission has established a common framework for public procurement aimed at ensuring *equal treatment and transparency, reduce fraud and corruption and remove legal administrative barriers to participation in cross-border tenders* [7]. While at the same time, open data on procurement contracts is increasing in volume and quality. Therefore opening space and opportunities for analytical frameworks that effectively evaluate the effectiveness and impact of public sector activities at different scales and dimensions comparatively. However, few studies have explored adequate methodologies that account for non-linearities in spending dynamics or examined the inference potential in

public procurement data [8, 9].

Here, in the present work, Urban Scaling Laws (USL), which are rooted in statistical physics and complexity sciences, are used to characterise the public procurement activity of Portuguese municipalities. USL [10–13] have been widely used across different disciplines to describe the relationship between socio-economic indicators in relation to the population size of population agglomerates. USL literature has invited a rethinking of existing urban planning frameworks and comparative indicators [14] while prompting researchers to look for the existence of underlying universal laws in cities and urban growth. Nevertheless, to the best of the authors knowledge, these procedures were never used to the study of public procurement in the published literature.

The next chapter introduces a brief context on public procurement and its most recent developments that made the present analysis possible. Together with an look over related work published both on procurement data analysis and municipal comparative studies. Chapter 3 continues with details on the methodology used namely Urban Scaling Laws, the data sources and all the processing steps taken. Chapter 4 shows the analysis of results demonstrating a characterization of municipality procurement activity compared with other Socio-Economic indicators. It is proposed the use of revealed deviation from the Urban Scaling Laws by each municipality, latter called Scale-Adjusted Indicators, as a mean to develop a data-driven comparative analysis and analyze municipalities from different standpoints. Chapter 5 concludes the work with some final remarks and a discussion of the results obtained together with some of the most critical limitations of the present work and the future directions that could arise from it.

CHAPTER 2

# RELATED WORK

## Background

To understand the already published work in the field or the lack of it, the current section starts with an introduction to modern Public Procurement especially focused on the European Union laws and guidelines. Followed by an analysis on approaches and ways procurement data has been analysed, to which fields and to what conclusions it has been applied. Adding a research on published work focused on comparative analysis mostly applied at the municipal level. This chapter aims to highlight the most relevant work published on this subject and raise the readers attention to the importance and novelty of the research that follows.

### Public Procurement

Public procurement stands as the process of acquiring goods or services from an external source by a public authority. The subject of procurement are goods or services which state authorities often cannot produce themselves. A common example would be a construction work in which a municipality does not have the in-house resources to do it as they are often big projects and not frequent. It stands as a fundamental tool for

governments to fulfill their duties and obligations to the general public.

Fair public procurement is rooted in the European Union since its conception. The Treaty on the Functioning of the European Union[15] defines as core functional principles, among others, the free movement of goods and services, the core subject of modern procurement. From there, policies and court rulings have favoured values like equality of treatment, transparency, mutual recognition and proportionality[16].

Public procurement has come a long way, from rigid pen and paper contracts mostly done at the national level to digital cross continent announcements. Relevant developments in procurement harmonization within the EU occur in 2004. The publication of directives 2004/18/CE and 2004/17/CE in which the EU advises member states to adhere to electronic procurement, and is often referred as the most influential directive that set in motion the adoption of e-Procurement and as a consequence open online procurement data by the member states. Delegating to each country its implementation but forcing all contracts above 6,242,000€ for public works contracts and 249,000€ for public supplies and service contracts[17] to be published in the Official European Journal (Supplement S of the Journal) and be digitally accessible at `https://ted.europa.eu`. In recent years these thresholds were reduced to increase the number of procurement reported to the EU and as a consequence, the each state's procurement transparency. The Portuguese Procurement Portal, has been made available in 2008, and aims to report, not only the contracts above the EU thresholds, but to report all procurement happening in the state. This led to a high quality portal that allows citizens to thoroughly inspect governmental contracts. Eventually leading to be selected as a case study in one of the latest, most detailed, reports by the Commission on the compliance and quality of public procurement systems[18]. The present work focuses on this data and will further describe it in the next chapter.

To provide a broader picture on procurement we quickly look at the world's biggest economy, the United States. Holding a long and solid history on public procurement. At first, very important in the defense areas and later on as a mechanism to stimulate the economy and certain

sectors such as the information technology procurement[19]. In 2014, the US passed the Digital Accountability and Transparency Act (DATA) Act of 2014, which calls for better transparency regarding federal expenditures. Federal procurement data is readily available at www.usaspending.gov. Meanwhile, at the local level, an uniform data source is still nonexistent [20].

Open procurement data, is still relatively new and datasets are generally small and not representative of all the public procurement market. In 2001, Thai [21] claimed most analysis being done were reports by agencies in charge of these platforms and not so much by the academic community or the general public. From the research conducted for this work there seems to be improvements but the general trend seems to continue. This also derives from the fact that open data is still scarce and with the increase and improvement of quality of the data more academic interest will be paid to e-Procurement data.

# Public procurement data analysis

Most analyses on public procurement often revolve around laws or specific procurement areas. On this chapter those will not be looked over as the focus here is on the data generated by these contracts and the procurement market as a whole. As previously mentioned, e-Procurement data can be used to characterize the expenses profile of Public Spending. While most analysis are conducted by organizations responsible for these contracts, there is also a topic of interest for researchers like Garcia et al [22] that explores the data for Spain to extract insights on how the government is spending public money and derive possible next analysis to the already existing data.

Fazekas et al. [23] use data on Public procurement in Hungary to signal potential *red flags* in public procurement behavior and from this infer a corruption indicator that can be used as a potential signal to policy

makers for errors or bad will in Public Procurement agents. With a dataset of 2 million e-Procurement contracts Gallego et al.[24] accesses the risk of malfeasance and possible inefficiencies in the process of procuring. In 2015, researchers looking at California bid contracts estimate the risk of collusion for high value procurement contracts [25]. And still on corruption, researchers have a looked at the risk of bunching within the EU and its effect in diminishing cost-effectiveness of public procurement [26].

Another common subject of analysis is the environmental/sustainability impact of procurement measures. One interesting study in this area is the one conducted in the Netherlands that using text mining techniques signal a potentially warming downwards trend in contracts referring sustainable public procurement[27].

In the last years the number and the different types of ideas to explore this data seem to be expanding. On a recent study, researchers from different organizations look at German procurement data and attempt to track the impact on innovation of e-Procurement, concluding that setting innovation as a criteria in opposition to have only lower price leads to innovation in the business sector even though is more effective for stimulating the diffusion of new technologies rather than promoting radically new inventions [28]. One of the important new points to have in consideration when using public procurement [7].

In 2019 researchers looking at Russian bid contracts assess the risk of bid rigging [29]. And in 2020 research have seemed to take e-Procurement in Switzerland ICT to ensure it follows sustainable procurement goals [30].

To finalize, the work presented by Ladislav et al. [8] represents most similar work that dives in to the public contract data, in this case Czech contracts. The authors apply methods from statistical physics to derive possible hypothesis on the functioning of the public procurement markets with a high focus on collaboration and assessing corruption risks.

# Comparative studies

The perfect allocation of resources to achieve results is impossible. Which does not imply that improvements to the current status quo are not possible. One such a way of improving this is by comparison. Looking at different actors and given a set of inputs and outputs compare them and identify good practices. This definition can be broadly applied in multiple contexts. The present section looks at recent comparative studies with a focus on local authorities comparison as this is the subject of the present work.

Comparative analysis of public practices is not new. In 2002 a join research from different universities access performance-based management systems with data of annual reports from nine municipalities from each country [31].

Portuguese decreasing population comparison recurring to municipal director plans [32] to evaluate how different municipalities are dealing with the decreasing population.

On a 8-year research Chinese researchers compare 8 cities in regards to efficiency of their water management system and it becomes obvious that the processes done by the cities of Shanghai and Beijing and leading to better result that the ones employed by the other 6 municipalities.[33]

To close this chapter, an important last mention is to the work done by Raan et. al [34] in which, using the same methodology as the one used in this paper (describe on the next chapter), the authors access the validity of urban agglomerations and compared them to municipality divisions. One important conclusion in the work is the importance of municipalities when compared for instance with urban agglomerations with the same size. From this we can see that there are multiple possible aggregations that we can use when looking at procurement contracts on section 3 the level choice is detailed the motives behind it are explained

The next chapter presents the data and the methodology used in our analysis.

Chapter 3

# Materials and Methods

## Urban Scaling Laws

In general, Urban Scaling Laws or USL models the relationship between an indicator, $Y$, and the population size, $X$, of a set of population agglomerates (*e.g.*, cities or urban areas) as a power-law, such as

$$Y \sim \alpha X^{\beta} \tag{3.1}$$

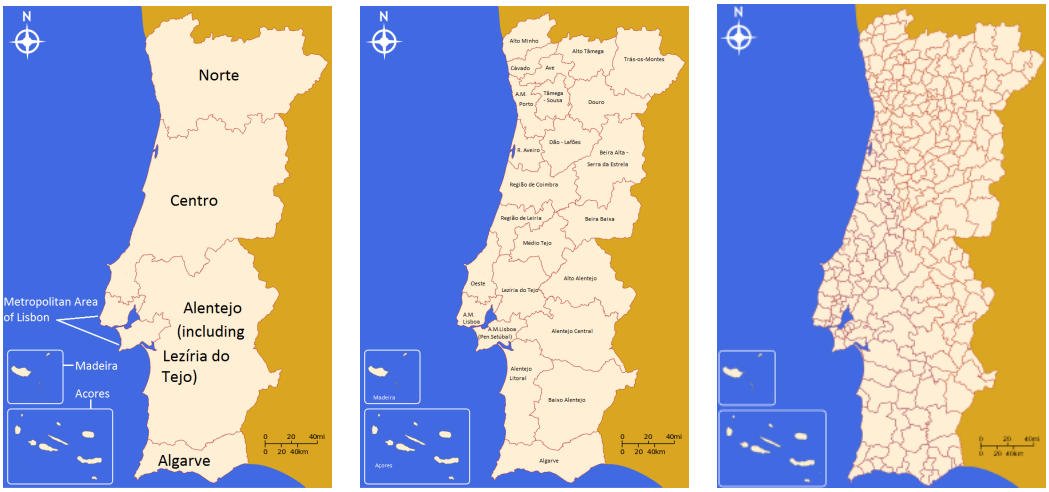
where $\beta$ is the scaling factor and $\alpha$ represents the natural baseline activity of a region [35, 36]. While several indicators – water consumption, housing, or jobs [37] – follow a linear relationship ($\beta = 1$), the more interesting cases are those in which $Y$ exhibits a super-linear ($\beta > 1$) or sub-linear ($\beta < 1$) relationship with $X$. Such cases identify particular indicators that either scale above (super-linear) or below (sub-linear) linear growth with increasing population size. Super-linear behavior is often observed in the region economic output [38–44], energy consumption and pollution [45–47], employment [48, 49] criminality [49–53], number of patents [44, 48, 52, 54], wages [52], employment in R&D [52] and urbanized area [48]. Sub-linear relationships often include the total length

of road network [40, 52], energy supply networks [55]. In other cases, like supply networks, exhibit sub or super linear behavior depending on the industry [55], and voter turnout [56]. In sum, population agglomerates present clear trade-offs between human activity outputs that increase from agglomeration, and infrastructure costs that diminish with agglomeration.

Previous works on USL have particularly, but not always, focused in cities [57]. However, cities do not necessarily define administrative governance boundaries, and it remains an open question to which extend cities' boundaries accurately represent an appropriate population aggregation unit [11, 58, 59]. For instance, *Arcaute et al* [37] uses information on commuting times to define new boundaries, raising questions about the accuracy of some scaling factors. Here, we focus on municipalities as they provide an appropriate balance between a regional unit of governance and a natural population agglomerate.

## Regional organization

Before presenting the data, an explanation on the way we have grouped the data in the way we have. This section presents an overview on Portugal's geographical organization and shows alternative divisions that could have been chosen. Portugal is a country with long-settled external borders and relatively slow-changing internal divisions. The first and obvious distinction is between mainland Portugal and the autonomous regions, the islands of Madeira and Açores. From there, several regional boundaries were developed that could have been used in the present analysis. Districts are a possible division that splits the continental into 18 regions established as they coordinate local services such as the police and national guard, social security center, or road administration. Although historically significant, they are now being faded out in favor of the European *Nomenclature of Territorial Units for Statistics* (NUTS) developed by Eurostat and employed in Portugal for statistical purposes. The NUTS division in Portugal represented in figure 3.1(a)-(b) show more




(a) NUTS2 division (b) NUTS3 division (c) Municipal division

Figure 3.1: Regional divisions in Portugal [1]

modern and recommend statistical division. NUTS III also represents Intermunicipal communities, which have a council and an assembly mainly constituted by elected members of the municipal assemblies.

Although these two divisions are statistically recommended and already have administrative power, they still lack two aspects deemed necessary for the present analysis, a significant amount of direct public contracts and direct elect government. Leaving two smaller regional divides: municipalities and parishes. Municipalities 3.1(c) represent the second-largest administrative division whose governance body is elected by universal suffrage. They are also the administrative division with the most stable regional boundaries and upon which city governance responsibility falls, thus, a suitable candidate to study the scaling behavior of procurement activity.

To support this, the previously mentioned study in the Netherlands also looks at different urban agglomerations in which among other conclusions they hint that the municipality organization performs better as compared to alternative organizations with the same population size[34].

[1] Images sourced from https://en.wikipedia.org/wiki/NUTS_statistical_regions_of_Portugal

# Data

Public procurement in Portugal is managed by *Instituto dos Mercados Públicos, do Imobiliário e da Construção* (IMPIC) and all data is shared on the online portal https://base.gov.pt.

The present dataset is a combined list of all contract data shared by the same institution on https://dados.gov.pt, the Portuguese open data portal. This data was shared following the Open Contracting Data Standard [2] an unified procurement format. Making it easier for researchers to explore theories in different countries datasets.

We focus our analysis on a data set comprising 930.513 contracts issued between January 2009 and December 2018. Each contract identifies the issuer that buys services/goods/works from the supplier. For each contract, we have collected the following features: issue date, the value of the contract (in euros), type of contract, and Fiscal Numbers of both the issuer and supplier. We analyze contracts issued by the 278 Municipalities that constitute Continental Portugal. We have not considered municipalities in Azores and Madeira archipelagos as they represent autonomous administrative regions. Since municipalities can constitute municipal companies, we have aggregated all municipalities and respective child companies into a single entity. The aggregation was hand-curated with support from the Yearly Financial Booklet of Portuguese Municipalities [60–62]. The pre-processing steps include:

1. Removing contracts with a value equal or smaller than one;
2. Identify the Fiscal Number of each Municipality to use as a primary key;
3. Aggregate municipal companies to the parent Municipality;
4. Discard all non Municipality related procurement contracts;
5. The value of contracts that involve more than one municipality was split equally among all issuers.

[2] https://www.open-contracting.org/data-standard/

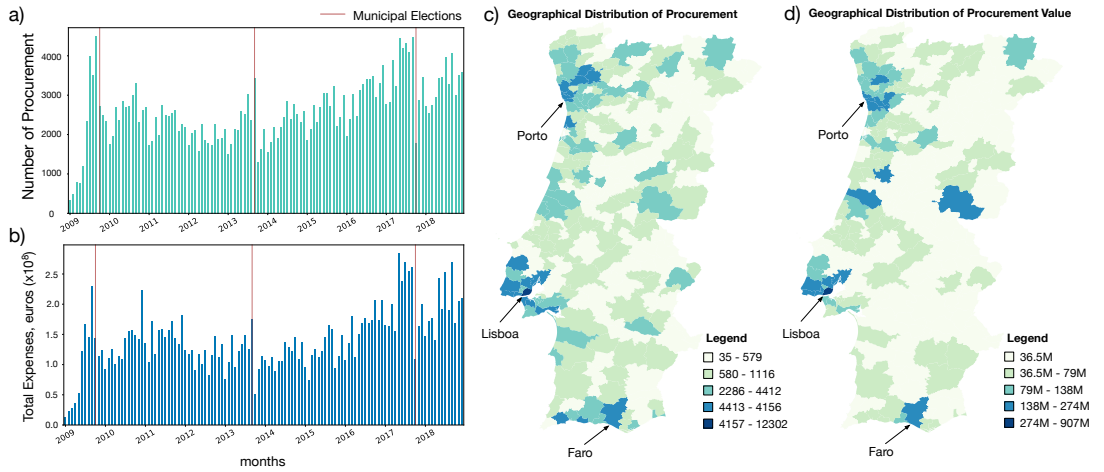



Figure 3.2: a) Number of monthly procurement issued between 2009 and 2019 by Portuguese municipalities. b) Total value in euros derived from procurement. In both a) and b), each bar corresponds to a month/year and vertical red lines indicate Municipal elections held nationwide. c) Spatial distribution of the total number of issued procurement by municipality. d) Spatial distribution of the total value spent in procurement.[3]

The final dataset comprises 310.819 contracts totaling a value of 16.9 Billion Euros. Panel a) of Figure 3.2 shows the monthly number of contracts issued, while panel b) shows the total value. Vertical lines indicate the dates of nation-wide municipal elections took place. Through visual inspection, it is possible to identify a tendency for municipalities to increase the number of procurement contracts issued in the months leading to elections. However, the same does not necessarily translate into an increase in expenditure. Figure 3.2c) and d) show the spatial distribution of the total number of contracts and the total value per municipality.

## Common Procurement Vocabulary

In the present work we analyze the procurement activity per municipality in total but also along the three contract types they might represent. These

[3] Azores and Madeira archipelagos are omitted and have not been used in the analysis. At the time the research was conducted data for 2019 was incomplete, contracts of that year were not included in the analysis and in the discussion of results.

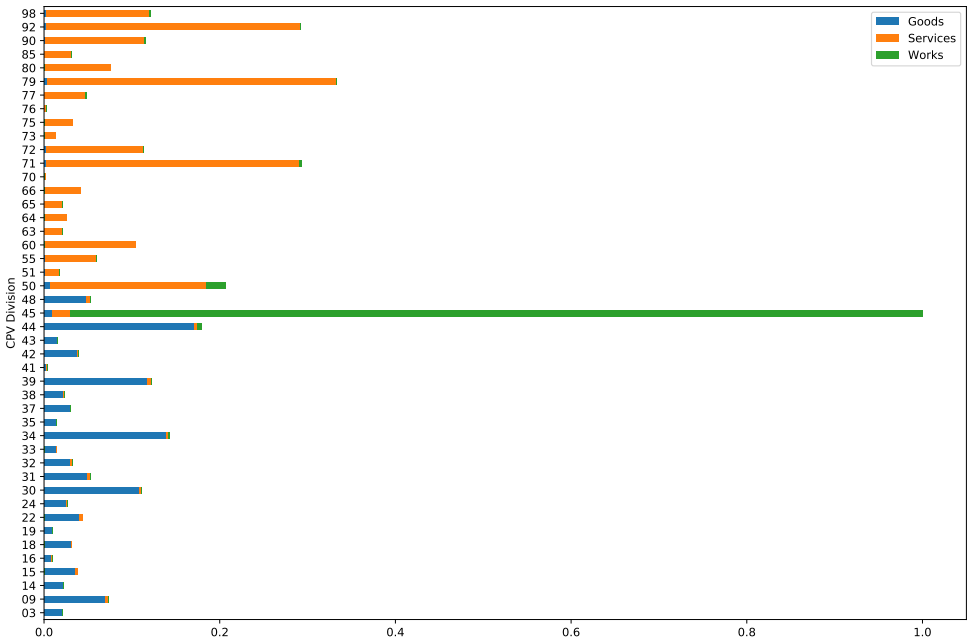



Figure 3.3: Volume of contracts per CPV, from a visual analysis it is possible to see the 3 types of contracts are representative even though service contracts are in higher number. The values are normalized with a division by the mean. (See in Table 1 in the Appendix for definitions)

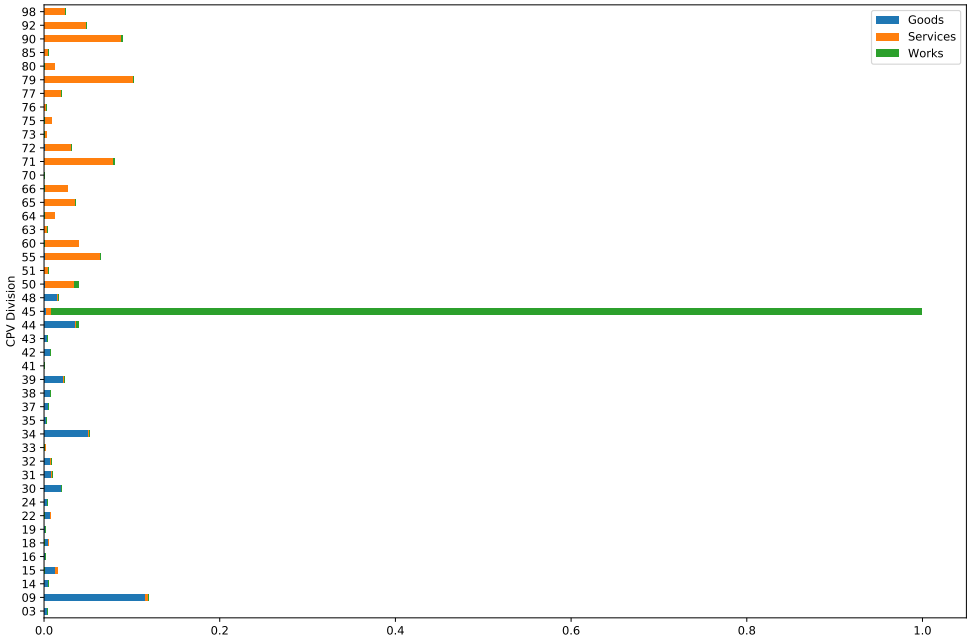



Figure 3.4: Procurement expenses per CPV, here we see works represents the highest part in municipalities expenses. The values are normalized with a division by the mean. (See in Table 1 in the Appendix for definitions)

Table 3.1: Description of the type of Public Procurement Contracts according to the UE public procurement guidelines.

| Contract type | Description |
|---|---|
| Work Contracts | Public contracts having as their objective either the execution, or both the design and execution, of works, for example building or civil engineering works such as a road or sewage plant. |
| Goods Contracts | Public contracts having as their object the purchase, lease, rental or hire purchase with or without option to buy, products such as stationery, vehicles or computers. |
| Service Contracts | Public contracts other than public works or supply contracts having as their object the provision of services such as consultancy, training or cleaning services. |

can be Work, Goods, or Service contracts. Table S2 summarizes the definition of each one of these types of contracts.

Moreover, each procurement contract is also classified according to the nature of the procurement transaction. It follows the Common Procurement Vocabulary (CPV) classification. The CPV was developed by the European Union and corresponds to an 8-digit and 4 level deep hierarchical classification. Table S3 lists the 2-digit (first level) of the classification as an example of the comprehensiveness of the classification the full table can be found in 5. In the main manuscript we decided to not perform the analysis at the CPV level because it is a very wide classification that also presents a very skewed distribution of procurements. That is, a small group CPVs represent the majority of the procurement contracts while in most CVPs we only have a few observations.

Figure S1 shows the distribution of the number and total value of Procurement Contracts by type along the first level of the CPV classification

Nonetheless, we have also conducted an exploratory analysis of the scaling behavior of the procurement data at the first level of the CPV classification. However, since in many cases municipalities might not have executed contracts in a particular CPV class, we have only included coefficients for estimations with at least 100 observations (100 municipalities). Coefficients are summarized in Table S4.

Each procurement is associated with a type of contract it represents,

which follows the standard classification from the European Commission [7] show in table 3.1 Hence, we have computed the total expenditure in procurement contracts per year for each municipality, as well as the total expenditure by procurement contract type. Moreover, since the yearly expenditure is rather noisy, we have applied a sliding window technique (moving average) of three years. In that sense, the procurement values at year $y$ correspond to an average of the values from years $y-2$, $y-1$, and $y$. The reported noise can have multiple sources. For instance, a municipality might issue a procurement for the execution of construction in one year that reflects in the forthcoming yearly budgets and thus decreases its construction activity in the following years.

The dataset is a tabular dataset with contracts as row and their properties as columns, from the contract properties we have extracted 5 important properties:

- `buyer.id` - Fiscal identifier of the procuring entity
- `tender.contractPeriod.startDate` - Start date of the contract
- `tender.value.amount` - The value of the contract
- `tender.mainProcurementCategory` - The main category, explained in Table 3.1
- `tender.items` - Column containing one or multiple common procurements codes(CPV) for the given contract. More information on the CPV can be found on Fig 3.(3–4)

Finally, we enriched the data set with additional indicators by municipality and year. From Pordata [63] we have sourced data on Social Integration Income; House Prices; Number of Public Workers; Total Births; Number of Large Corporations; Number of Divorces; Amount of Credit; Number of Medical Doctors; Number of Culture Attendees; Imports and Exports Volumes; and Environment Expenses. While on

Table 3.2: Socio Economic variables description

| Dataset | Years | Missing values | Public | Unit | Mean | Std | Min | Max |
|---|---|---|---|---|---|---|---|---|
| Imports | 2009-2018 | 0 | Y | Euro | 2.03E+08 | 1.09E+09 | 0 | 1.83E+10 |
| Exports | 2009-2018 | 0 | Y | Euro | 1.59E+08 | 4.66E+08 | 0 | 7.44E+09 |
| Social Integration Income | 2009-2018 | 0 | Y | Euro | 1221 | 2755 | 0 | 31315 |
| Energy Consumption | 2009-2017 | 0 | Y | kWh | 22101 | 34272 | 1226 | 383252 |
| Total births | 2009-2018 | 0 | Y | Nº | 360 | 700 | 0 | 18276 |
| Doctors | 2009-2018 | 0 | Y | Nº | 158 | 650 | 0 | 9573 |
| Large Corporations | 2009-2017 | 0 | Y | Nº | 4 | 18 | 0 | 285 |
| Culture Atendees | 2009-2018 | 0 | Y | Nº | 33086 | 183685 | 0 | 3006910 |
| Divorces | 2009-2018 | 0 | Y | Nº | 67 | 135 | 0 | 2143 |
| Amount of Credit | 2009-2017 | 0 | Y | Euro | 7.44E+08 | 8E+06 | 0 | 8E+06 |
| House Prices | 2009-2018 | 0 | Y | Euro | 52647 | 48297 | 1208 | 575900 |
| Public workers | 2009-2017 | 0 | Y | Nº | 428 | 657 | 49 | 10106 |
| Environment Expenses | 2009-2018 | 0 | Y | Euro | 2038 | 5448 | 0 | 86858 |
| Total crime | 2009-2017 | 0 | Y | Nº | 1259 | 2963 | 15 | 4250 |
| Self-Reported Gross Income | 2011-2017 | 0 | N | Euro | 289071 | 672063 | 8574 | 9416926 |
| ATM withdrawals | 2011-2017 | 0 | N | Euro | 8.8E+07 | 2E+08 | 3E+06 | 3E+09 |
| Credit given for housing | 2011-2017 | 0 | N | Thousands of euro | 327468 | 1E+06 | 7356 | 2E+07 |
| Municipal Property Tax | 2011-2017 | 0 | N | Thousands of euro | 4800 | 10072 | 40 | 118153 |
| Average Income of a full time worker | 2011-2017 | 0 | N | Euro | 895 | 163 | 673 | 2331 |
| Municipality employees | 2011-2017 | 0 | N | Nº | 7167 | 19149 | 178 | 295474 |
| Volume of Business (Accomodation) | 2011-2017 | 90 | N | Euro | 2.6E+07 | 8.3E+07 | 4E+05 | 2E+09 |
| Volume of Business (Catering) | 2011-2017 | 0 | N | Euro | 1.6E+08 | 3.4E+08 | 2E+06 | 5E+09 |
| Volume of Business (Retail) | 2011-2017 | 361 | N | Euro | 1.6E+08 | 3.4E+08 | 2E+06 | 5E+09 |

INE[4] [64] – ATM Withdrawals, Municipal Property Tax, Volume of Business in Accommodation, Catering, and Retail; Individual Gross Income; Average Salary of Full-Time Workers;

[4]Instituto Nacional de Estatística

Chapter 4

# Results Discussion

The present analysis starts by comparing the estimated scaling coefficients from municipal procurement activity with those estimated from a wide set of socio-economic indicators. The coefficients have been estimated independently for each year between 2011 and 2018. Figure 4.1a shows the average coefficient (Y-Axis) per indicator (X-Axis) with error bars representing the standard deviation.

In general the obtained scaling coefficients are inline with previous findings in the USL literature, thus supporting the choice of analysis at the municipality level. Namely, a super-linear behavior is observed for the volume of imports ($\beta = 2.05 \pm 0.12$) and exports ($\beta = 1.79 \pm 0.10$), number of medical doctors ($\beta = 1.38 \pm 0.01$), volume of business from retail except car sales ($\beta = 1.21 \pm 0.01$), amount of credit ($\beta = 1.21 \pm 0.04$), municipal property tax ($\beta = 1.19 \pm 0.05$), number of divorces ($\beta = 1.18 \pm 0.02$), total volume of house mortgages ($\beta = 1.17 \pm 0.02$), volume of business from catering ($\beta = 1.16 \pm 0.03$), number of workers ($\beta = 1.16 \pm 0.01$), number of births ($\beta = 1.15 \pm 0.02$), ATM withdrawals ($\beta = 1.14 \pm 0.01$), self-reported gross income ($\beta = 1.10 \pm 0.01$), and reported crime ($\beta = 1.08 \pm 0.04$). Linear scaling is observed for total volume of business from accommodation ($\beta = 0.99 \pm 0.05$). Sub-linear scaling is observed

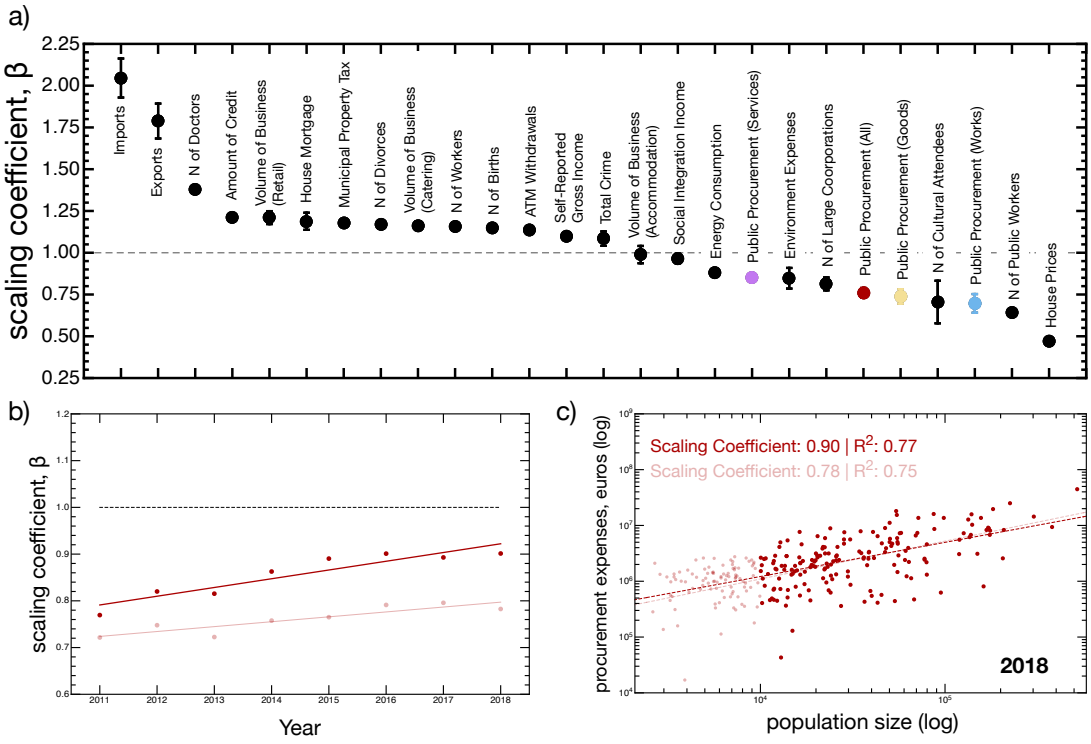



Figure 4.1: a) Average scaling coefficients for multiple socio-economic metrics (Black) and all procurement expenses (red). Moreover, we also show the coefficients obtained for the different types of procurement contracts: works (blue), goods (yellow), and services (purple). Error bars indicate the standard deviations of estimated coefficients for the different years. Panel b) shows the yearly changes in the scaling coefficients for procurement activity. Panel c) exemplifies the identified relationships between the procurement expenditure (euros) and population size for the year of 2018. In panels b) and c) we highlight the results for municipalities with more than $10^4$ residents.

for energy consumption ($\beta = 0.88 \pm 0.006$), social integration income ($\beta = 0.97 \pm 0.03$), environment expenses ($\beta = 0.84 \pm 0.06$), number of large corporations ($\beta = 0.81 \pm 0.04$), number of culture attendees ($\beta = 0.70 \pm 0.13$), number of public workers ($\beta = 0.70 \pm 0.06$), and house prices ($\beta = 0.47 \pm 0.02$).

Figure 4.1b–c explores more in detail the results obtained from the total procurement expenses per municipality. Figure 4.1b shows the yearly change in the scaling coefficient, which exhibits an upward temporal trend. Light colored points indicate scaling coefficients estimated

when considering all municipalities, while dark-colored considers only municipalities with a population size larger than $10^4$. Figure 4.1c shows a representative example of the scaling behavior from the year 2018. Further, it shows the impact of including (lighter) or not (darker) municipalities with a population lower than $10^4$ in the estimation. In all cases, the coefficient shows a sub-linear relationship between the total public procurement expenditure and population size.

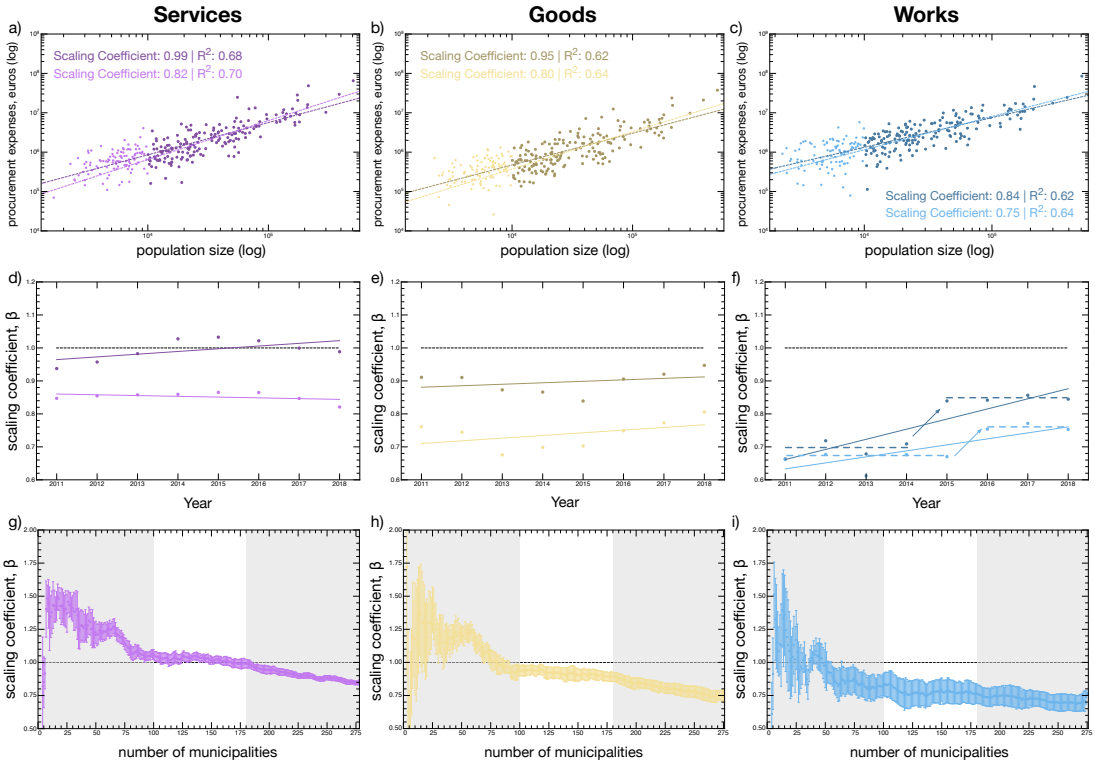



Figure 4.2: Panels a–c) Scaling relationships between total procurement expenses, by type, in 2018 and population size. Panels d–e) Scaling coefficient per year and type of expenses. Panels g–i) show the estimated scaling coefficient for each contract type when only the $n^{th}$ most populated municipalities are used to estimate the scaling coefficient. In other words, is as if we are removing the least populated municipalities from the right to the left. Error bars indicate the standard deviation of the estimated scaling coefficient. In panels a–e) lighter colors indicate the analysis conducted on all Municipalities, darker colors on the subset of municipalities with a population greater or equal to $10^4$. Each column indicates results for a different type of contract: Services (left); Goods (middle); and Works (right). In Panels d–f) lines indicate the best linear model but should only serve as a guideline.

Figure 4.2 extends the analysis done in Figure 4.1b and Figure 4.1c to different procurement contract types: Services, Goods, and Works. Like in Figure 4.1. Light colors refer to the entire set of municipalities, while darker colors represent the sample of municipalities with a population size larger than $10^4$. Figure 4.2a–c shows the scaling relationships in the year of 2018 for all three types of procurement contracts. As with the results in Figure 4.1c, Goods and Works contracts show an evident sub-linear scaling. In contrast, Services show an almost linear relationship if only the most populated municipalities are considered but a sub-linear relationship when the entire set is under consideration.

Moreover, in Figure 4.2d–f, we show that, unlike the results in Figure 4.1b, the yearly upward trend of the scaling coefficient is absent in Goods and Works contracts. However, for Works contracts, exhibit a transition, around 2014/16, between two regimes. Such behavior is not necessarily surprising. The transition matches the time when Portugal left the bailout program and can be an indication of the impact that the program had on public contracts. However, a causal relationship between the reported phenomena and its context requires a more extensive analysis, which is not within the scope of this work.

Figure 4.2g–i explores the impact of removing (from right to left) sequentially the least populated municipalities in the estimation of the scaling coefficient (Y-axis). We expect two limiting scenarios: First, when we only consider the most populated municipalities, large variations on the estimated scaling coefficients as the addition/removal of observations will impact significantly in the regression; Secondly, given the over-representation of small municipalities and the fact that we are using a logarithmic scale, removing smaller municipalities should lead to small corrections in the scaling estimation. We identify the domain of these two scenarios with a shaded background in Figure 4.2g–i. However, in between these two limiting scenarios, we observe an interval where the scaling coefficient is stable and resilient to the addition/removal of observations. In that regime, we qualitatively observe the same relationship between the estimated coefficients of the three types of

contracts: Services with higher coefficients close to one and Works has the lowest coefficients around 0.75.

In the remaining of the manuscript, we will focus our analysis on the entire set of municipalities. Such choice provides a more comprehensive picture of the regional dynamics at play among Portuguese municipalities.

## Scale-Adjusted Indicators

One major challenge when developing a comparative analysis of regional data relates to how an indicator scales along the dimension of analysis (e.g., region area, population size, etc.). For instance, it is common to compare regions on a *per capita* basis. However, such scaling/assumption is only accurate if the indicator under study scales linearly with population size. Since that is not the case for most indicators, see Figure 4.1, we can end up with erroneous conclusions. In that sense, Urban Scaling literature proposes using, instead, the residuals of each region from the specific scaling law as a reference model. In our case, the residuals indicate which municipalities spend more/less in procurement contracts according to what is expected from their population size.

In that sense, we follow by estimating the so-called *Scale-Adjusted Indicators* (SAI) [10, 53, 65] as a means to quantify deviations of each municipality procurement activity from what would be expected from its population size. The SAI correspond to the residuals, which are computed as

$$SAI_{i,t} = log_{10}\frac{Y_{i,t}}{Y(N_{i,t})} \tag{4.1}$$

where $Y_{i,t}$ is the observed expenditure of municipality $i$ on year $t$, and $Y(N_{i,t})$ is the predicted value given the population size of such municipality. Visualized on the dashed red lines in figure 4.3. Unlike *per capita* indicators, the SAI are dimensionless and independent of population size [10, 53, 65]. The SAI capture human and social dynamics specific to a given place and time. It is a true local measure that allows direct comparison between two regions and provides meaningful comparative

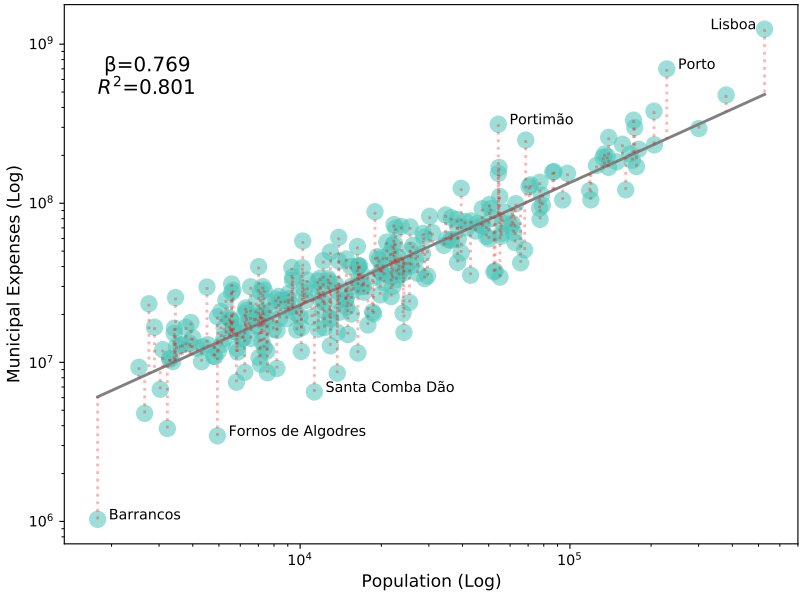



Figure 4.3: Scalling law for total public procurement over all the years and categories. Scale-Adjusted Indicators highlighted in red dashed lines.

information between population agglomerates and regional governance bodies. One interesting application of the SAI has been in the development of rankings that allow quantifying an indicator of interest [10]. In the Supporting Information, we provide a discussion of such an application to the procurement activity in Portugal.

Figure 4.4 above shows the distribution of SAI obtained for different types of contracts for 2018 and the best fit Normal Distribution for the SAI estimated per year. In all but one case, SAI are Normally Distributed. Moreover, the SAI are uncorrelated with population size and show no heteroscedasticity.

## Ranking Municipalities

One common, and well known, application of the SAI concerns the ranking of regions according to their activity. Since the SAI is dimensionless and already correct for population differences, they provide an interesting reference to identify which municipalities have spent more or less that their intrinsic capacities predict. Figure 4.6 shows the ranking for all 278

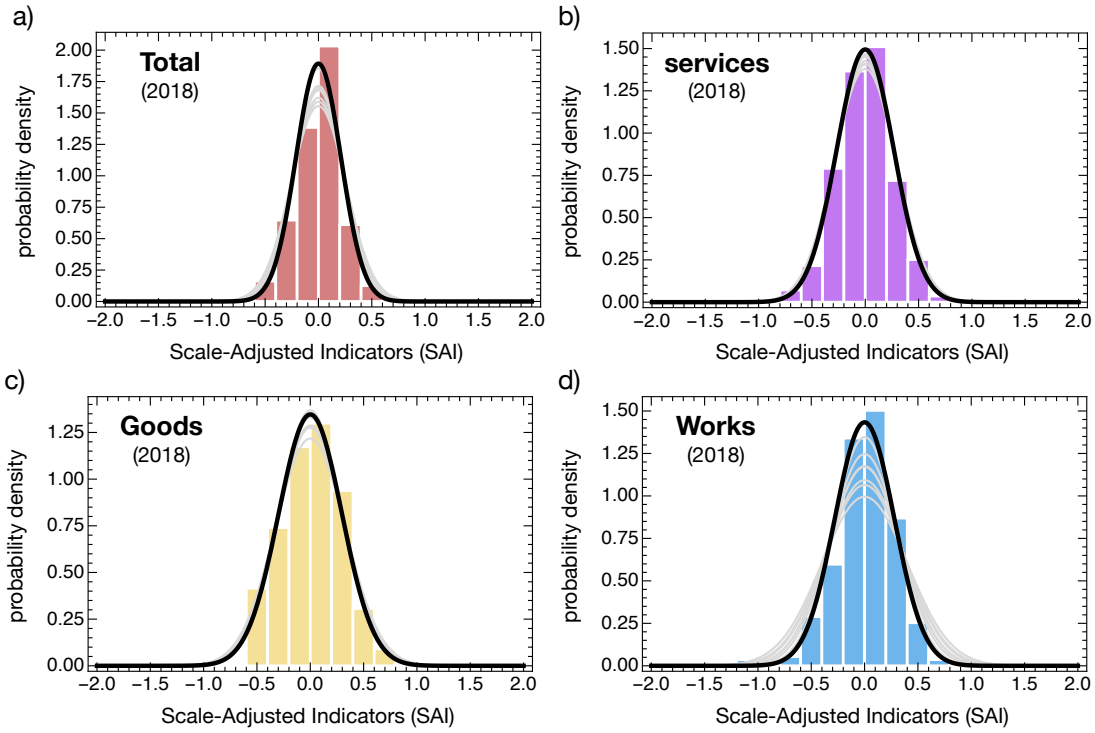



Figure 4.4: Distributions of Scale-Adjusted Indicators (SAI). Bars show the distribution of SAIs for 2018; curves show the best fitted Normal Distribution to the SAI data for each year. Except for the observations for one year and one type of contract (Goods in 2014) the hypothesis that SAI follow a normal distribution cannot be disproved using Cramér–von Mises criterion at the p-value = 0.05 threshold. .

municipalities on the three procurement contracts types in the year of 2018. A set of relevant municipalities are highlighted plus the top three municipalities.

We can see several cases of municipalities with positive SAI in one procurement type that have negative on another. This naturally raises questions on the richness of procurement profiles that exist and the potential to characterize municipalities by their profile of public procurement.

One important take from the rankings it to see that big municipalities like Porto and Lisboa seem to yield positive scaling in all three types of contracts, possibly denoting a tendency for central administrative areas to have disproportionately large spending budgets. This analysis was only done for the year of 2018 and to strengthen these claims a deeper yearly

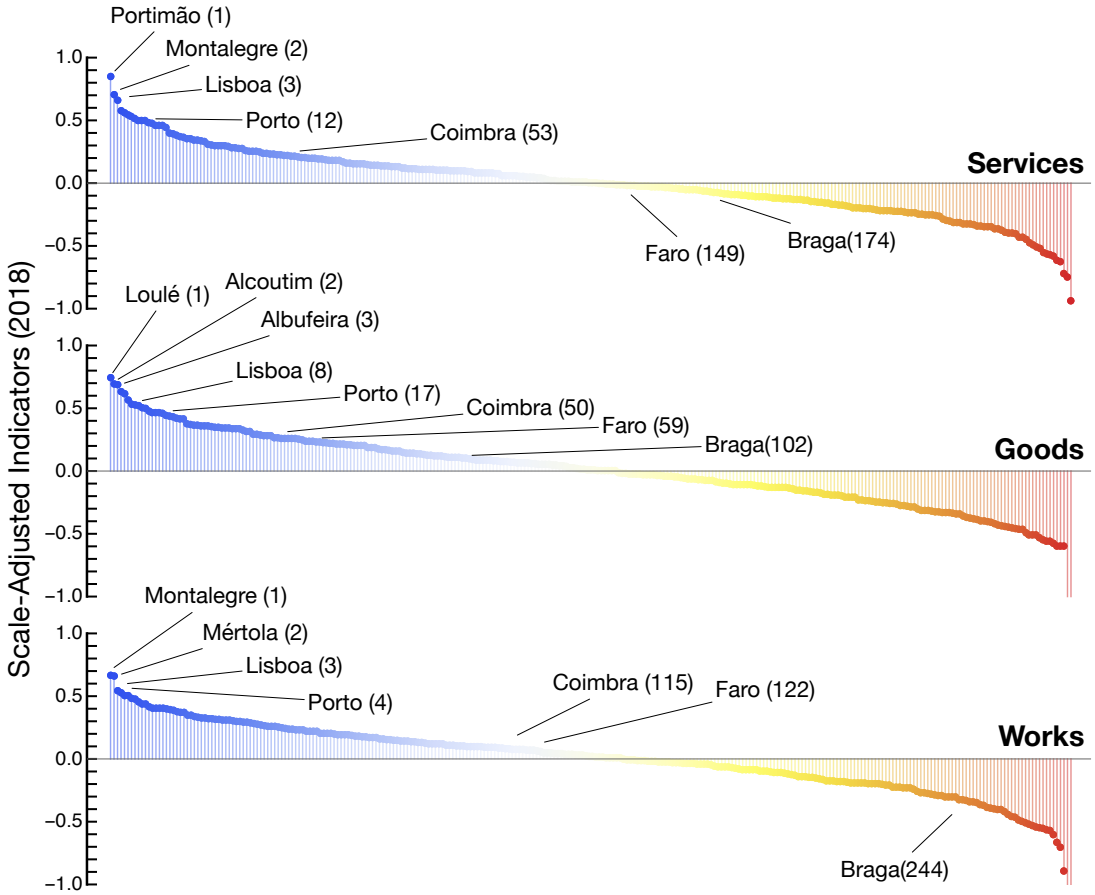



Figure 4.5: Ranking of Procurement Activity Portuguese Municipalities on the three different types of contracts under analysis (Services, Goods, and Works) using the Scale-Adjusted Indicators.

analysis would be required.

## Procurement Activity and Regional Economic Activity

We start by inspecting how procurement activity relates to regional economic activity, which we capture through a wide range of indicators commonly used to estimate purchasing power [64]. To that end, we estimate the Pearson correlation between the SAI associated with procurement activity by contract type – Services, Goods, and Works – and the SAI obtained from regional economic indicators such as: the average salary of full-time works; self-reported individual gross income; total volume of ATM withdrawals; total value collected from Municipal property tax; the number of workers; total amount of loans; Volume of Business

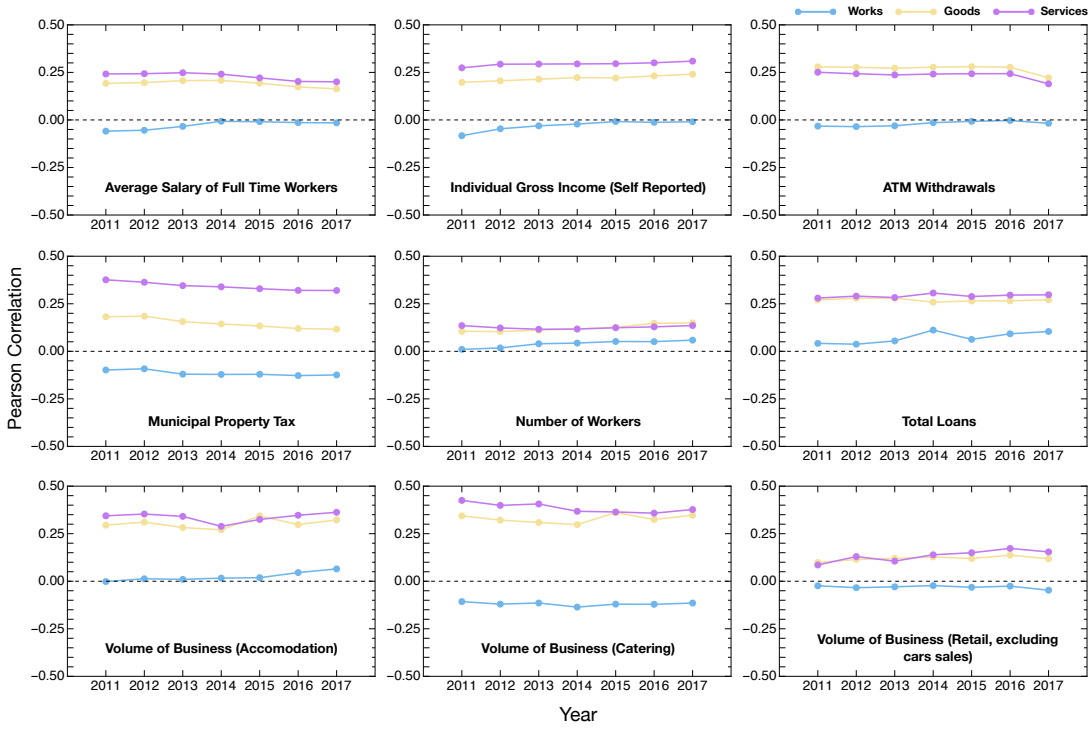



Figure 4.6: Correlations between the Scale-Adjusted Indicators of Public Procurement Activity and Regional Indicators of Economic Activity.

activities in Accommodation, Catering, and Retail (excluding car sales).

Figure 4.6 shows the yearly correlations between the procurement SAI and regional indicators. In all panels, the Y-axis indicates the Pearson correlation, and X-axis represents the year of analysis. Each curve's color indicates the type of procurement contract, and each panel depicts the results for a particular regional economic activity indicator. Surprisingly, Works procurement contracts exhibit null to negative correlation in most indicators. Exceptions are in the number of workers and the total volume of loans. This interesting finding raises questions on the impact of public procurement work contracts as an effective policy instrument that we believe deserves future work. These results show that different types of public procurement might spill over to different economic dimensions in different ways. In contrast, Services and Goods procurement contracts show a stable positive correlation with most indicators.

More importantly, these results show that there exists a link between procurement activity and the regional economy. In that sense, such

economic indicators can be used effectively as monitoring proxies for the evaluation of public policy programs. Moreover, the short analysis also supports the potential of using procurement SAI as an explanatory variable in models that look to understand the importance and relevance of different types of public procurement activity in the local economy.

## Regional Divide

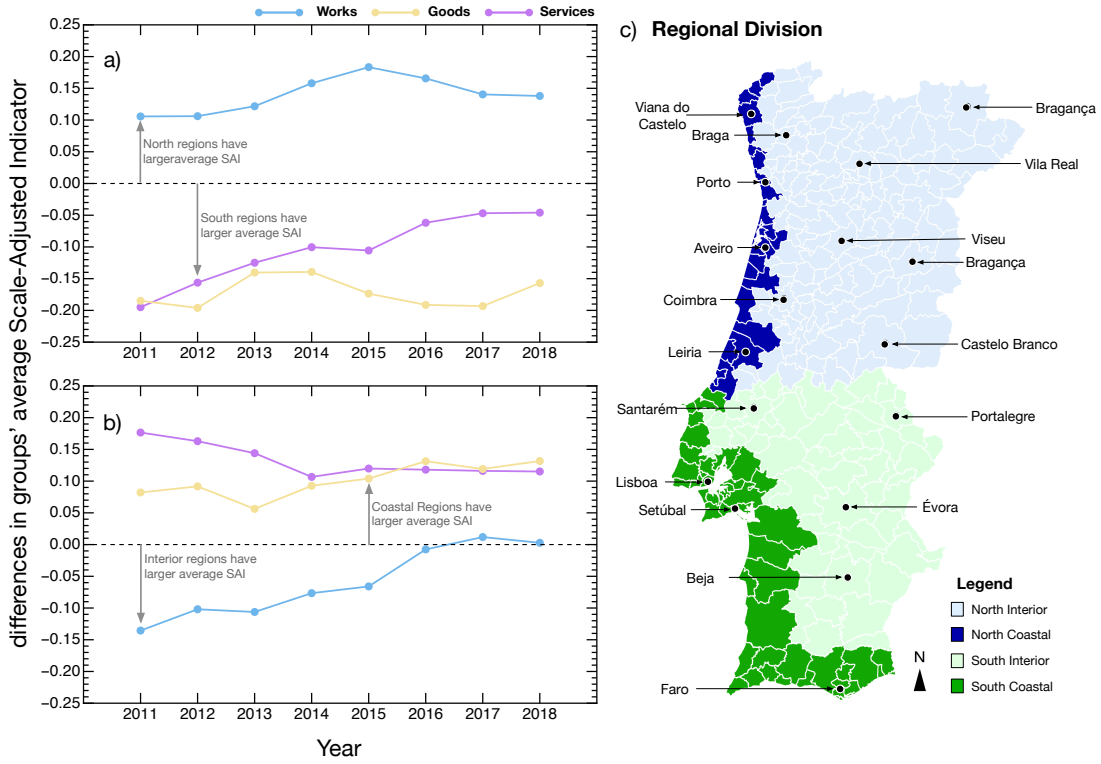



Figure 4.7: Yearly Differences in the Scaling-Adjusted Indicators between different groups of Portuguese Municipalities. Panel a) shows the differences between North and South, and Panel b) shows the differences between Coastal and Interior. Panel c) shows the Portuguese municipalities colored according to the groups they have been assigned to. District capitals are indicated. Panels d–f show the Scale-Adjusted Indicators of each municipality for each procurement contract type in the year of 2018. Minimum and maximum of the color range is set to the maximum absolute Scale-Adjusted Indicator observed.

One application of Scale-Adjusted Indicators is to identify and compare patterns between groups of regions. By helping to identify commonalities but also exceptions, it can aid policymakers in pushing the adequate policies for regional development [66]. In that sense, Portugal is marked by different regional development profiles related to the natural, social, and economic diversity that loosely runs from North to South and its urban system anchored on two main metropolitan areas (Lisboa and Porto). On the other hand, the country deals with substantial challenges stemming from significant migration movements towards coastal regions (and the ongoing decline in population growth) that, in time, amplified territorial disparities mainly marked by the dichotomy of Interior/Coastal regions [67–71].

In light of such regional realities in Portugal, it is interesting to investigate whether public procurement activities reveal some of these well-known dichotomies, which means if differences among the described groups exhibit different and distinguishable patterns. To that end, and as a first exercise, we grouped municipalities according to whether they are located in the Coast/Interior or the North/South of Portugal[1]. We defined as Coastal municipalities all those that have a coastline or that are enclaves of municipalities with a coastline, else they are categorized as Interior. Moreover, we used the coordinates of each municipality capital as a point of reference to classify them as being in the North or South. In particular, we classified as North the 140 municipalities whose city coordinates are the northernmost; the remaining 138 are classified as being in the South. Figure 4.7c shows the classification of each municipality.

Figure 4.7a–b compares the differences ($\Delta$) in the procurement SAI activity between different groups of municipalities. In particular, Figure 4.7a compares North and South municipalities ($\Delta = \text{SAI}_{\text{NORTH}} - \text{SAI}_{\text{SOUTH}}$) and Figure 4.7a compares Coastal and Interior municipalities ($\Delta = \text{SAI}_{\text{COASTAL}} - \text{SAI}_{\text{INTERIOR}}$).

[1]It is noteworthy to mention that there is no generally agreed definition of these regional groups, in that sense in this work we take the most neutral definition possible. However, using this methodology, further regional definitions can be tested in future work.

In Figure 4.7a a positive/negative difference means that Northern/-Southern municipalities exhibit in average larger/smaller SAI than their counterpart. From Figure 4.7a we observe that there is a clear dichotomy that characterized by the common perceptions and differences between Northern and Southern regions, in that, Northern municipalities tend to exhibit larger average SAI in Works while Southern are characterized by larger SAI in Services and Goods. These patterns remain qualitatively the same, although Services procurement contracts seem to been converging to parity between the two groups.

In Figure 4.7b a positive/negative difference means that Coastal/Interior municipalities exhibit in average larger/smaller SAI than their counterpart. Once again, results show that there are clear differences between both these regions, in particular Coastal municipalities tend to have higher SAI in Goods and Services procurement contracts, while Works contracts have evolved from being larger in the Interior to reach parity since 2016.

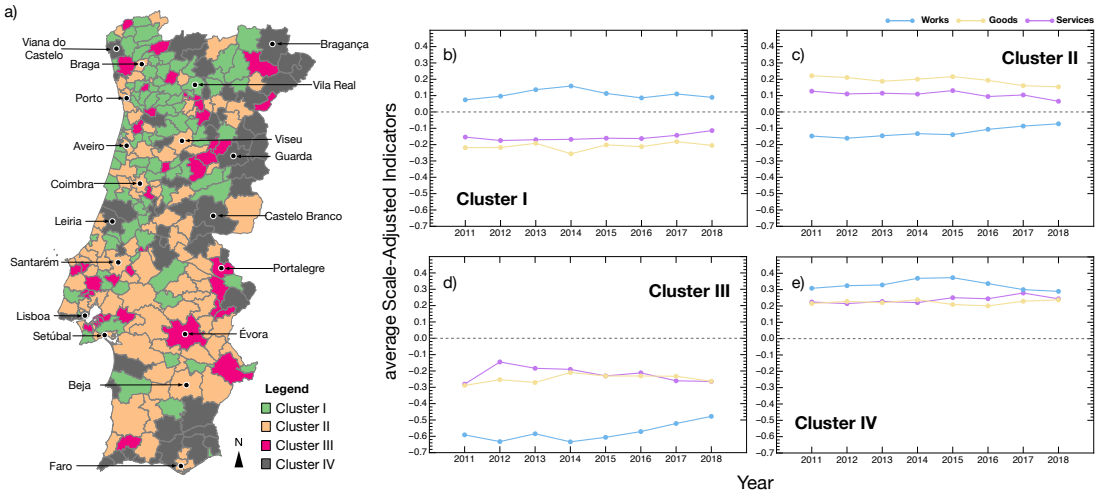



Figure 4.8: Clustering of Municipalities according to the Scale-Adjusted Indicators patterns. Panel a) associates municipalities to a cluster. Panels b–e) show the average SAI in the different procurement contract types – Works (blue), Services (purple), and Goods (yellow) – allowing to characterize the procurement activity patterns of each cluster.

Figure 4.7d–f shows the spatial distribution of the 2018 SAI across the Portuguese municipalities for each type of procurement contracts. We set

the color range to be the same in all three cases. Interestingly, the distribution of SAI does not map directly into the regional groups that we have analyzed above; that is, we cannot clearly distinguish between North/-South and Coastal/Interior. Instead, they show a more heterogeneous spatial distribution.

Grouping municipalities can provide interesting insights into existing differences among regions. In that sense, the SAI can be the basis to identify clusters of municipalities with similar procurement activity patterns. To that end, we clustered municipalities using the K-Means algorithm to identify the four clusters of municipalities with similar activity patterns. We performed the cluster by considering that each observation consisted of the estimated SAI of each type of procurement per municipality per year. See the Supplementary Information for more information about the clustering procedure.

We have identified four main groups of municipalities that we refer to as clusters I, II, III, and IV. Figure 4.8a shows the spatial distribution of clusters estimated from procurement activity. It does not stem from pre-conceived perceptions of historical, geographical, or demographic nature and translates the information revealed by the municipalities' procurement activity. Naturally, it presents clusters with higher spatial variance, contrary to the analysis conducted above. Figure 4.8b–e shows the yearly average SAI for each procurement type in each cluster. Cluster I is characterized by average positive SAI in Works and average low negative SAI in Services and Goods. Cluster II is characterized by strongly negative SAI in Works and nearly null SAI in Services and Goods. Cluster III is characterized by municipalities with strongly negative SAI in all three types of contracts. Finally, cluster IV is defined by municipalities with moderately positive SAI in all procurement contract types. Clusters I and IV show, respectively, a predominance of Northern and Southern municipalities. Clusters II and III are more geographically disperse.

The SAI can thus help identify different regions with different activity patterns. However, a more robust analysis of the factors underlying such differences is needed.

CHAPTER 5

# CONCLUSION

It is often challenging to develop accurate indicators when most of the times they do not scale linearly with, for example, population size. We proposed using methods from Urban Scaling Laws to analyze procurement activities among 278 Portuguese municipalities and by contract type.

We have characterized the scaling coefficient of procurement activity and put it at a glance with various other indicators. Municipal procurement activity tends to scale sub-linearly with population size, meaning that increasing the population size lowers the value spent *per capita* in public contracts. Such behavior is true for both the total value spent in public procurement and specific types of contracts.

Looking at the scaling coefficients' yearly variation, we identified a trend that suggests an increase in the coefficient that is mostly associated with a regime transition in the Works procurement contracts, whose coefficient jumped from $\approx 0.7$ to $\approx 0.85$ around 2014/16.

Moreover, looking at individual deviations from the scaling laws, we have explored its usefulness in characterizing different regional groups' profiles. In that sense, we have shown that the SAI captures interesting

differences between regional groups – North/South and Coastal/Interior – of municipalities. The SAI also provides an alternative to estimate the adequate groups in terms of similarity of procurement activity. We show that the resulting groups/clusters of municipalities present different procurement activity patterns and a non-trivial organization in the Portuguese geography.

These last results demonstrate the validity of this type of analysis for policymakers and researchers alike interested in using comparative analysis, when possible data-driven, to understand better the impact of their policies in populations.

The results here presented in further detail are summarized in manuscript submitted for the PLOS ONE under the same name *Scaling Behavior of Public Procurement Activity*[72] and at the moment of submission of this thesis, it was in the state of waiting for review.

## Limitations and Future Work

The results demonstrated here do not show a way that policymakers should act or a preferred way in public procurement spending. What is instead shown is the novelty of the data-driven analysis on public procurement and, more specifically, using Urban Scaling Laws.

During this analysis, some extreme values were found where municipalities spend much more or less than the calculated coefficients' expected value. Meanwhile, this could potentially be a signal of malfeasance or failure to report expenses. There is also the possibility that not all municipal fiscal identifiers were contained on the dataset, and it lead to missing data. Ongoing work aims to develop a more robust model to understand the link between public procurement activity at the regional level and economic development. Such work should develop a more robust model that allows controlling for other relevant factors [73]. Moreover, future work should also extend this analysis to other countries and regions, particularly European public procurement repositories. The

latter would allow us to validate the identified similarities and differences in behaviors across countries with different processes and cultures.

As open data is slowly becoming more ubiquitous and it gets more common for public bodies to share information, research like this will be even more essential and a useful tool to measure the impact of different administrations and policies.

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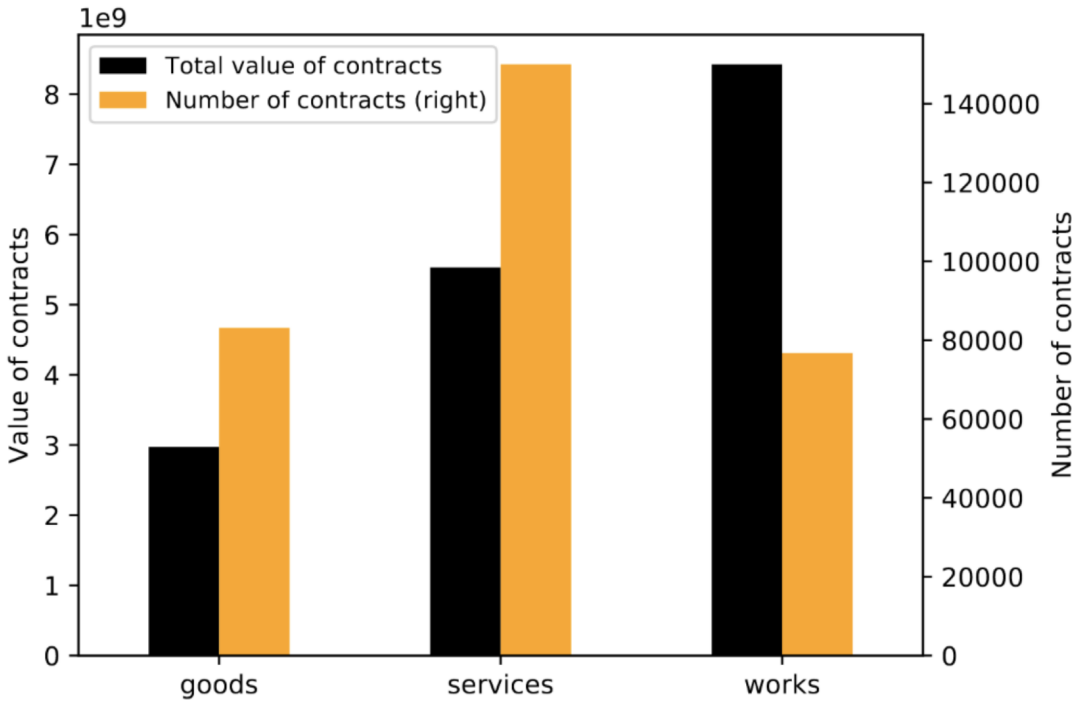
# Value and total number of contracts per contract type



# CPV FIRST LEVEL DIVISIONS

| id | description |
|---|---|
| 03 | Agricultural, farming, fishing, forestry and related products |
| 09 | Petroleum products, fuel, electricity and other sources of energy |
| 14 | Mining, basic metals and related products |
| 15 | Food, beverages, tobacco and related products |
| 16 | Agricultural machinery |
| 18 | Clothing, footwear, luggage articles and accessories |
| 19 | Leather and textile fabrics, plastic and rubber materials |
| 22 | Printed matter and related products |
| 24 | Chemical products |
| 30 | Office and computing machinery, equipment and supplies except furniture and software packages |
| 31 | Electrical machinery, apparatus, equipment and consumables; lighting |
| 32 | Radio, television, communication, telecommunication and related equipment |
| 33 | Medical equipments, pharmaceuticals and personal care products |
| 34 | Transport equipment and auxiliary products to transportation |
| 35 | Security, fire-fighting, police and defence equipment |
| 37 | Musical instruments, sport goods, games, toys, handicraft, art materials and accessories |
| 38 | Laboratory, optical and precision equipments (excl. glasses) |
| 39 | Furniture (incl. office furniture), furnishings, domestic appliances (excl. lighting) and cleaning products |
| 41 | Collected and purified water |
| 42 | Industrial machinery |
| 43 | Machinery for mining, quarrying, construction equipment |
| 44 | Construction structures and materials; auxiliary products to construction (except electric apparatus) |
| 45 | Construction work |
| 48 | Software package and information systems |
| 50 | Repair and maintenance services |
| 51 | Installation services (except software) |
| 55 | Hotel, restaurant and retail trade services |
| 60 | Transport services (excl. Waste transport) |
| 63 | Supporting and auxiliary transport services; travel agencies services |
| 64 | Postal and telecommunications services |
| 65 | Public utilities |
| 66 | Financial and insurance services |
| 70 | Real estate services |
| 71 | Architectural, construction, engineering and inspection services |
| 72 | IT services: consulting, software development, Internet and support |
| 73 | Research and development services and related consultancy services |
| 75 | Administration, defence and social security services |
| 76 | Services related to the oil and gas industry |
| 77 | Agricultural, forestry, horticultural, aquacultural and apicultural services |
| 79 | Business services: law, marketing, consulting, recruitment, printing and security |
| 80 | Education and training services |
| 85 | Health and social work services |
| 90 | Sewage, refuse, cleaning and environmental services |
| 92 | Recreational, cultural and sporting services |
| 98 | Other community, social and personal services |

# Scaling coefficients per CPV

| CPV | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|---|---|
| 03 | - | - | - | - | - | - | - | 0.37 | 0.53 | 0.29 |
| 09 | - | 0.42 | 0.47 | - | 0.32 | - | - | - | - | 0.50 |
| 14 | - | 0.06 | - | - | - | - | - | 0.45 | - | 0.31 |
| 15 | - | - | - | - | - | - | 0.29 | 0.26 | 0.44 | 0.30 |
| 16 | - | - | - | - | - | - | - | - | - | - |
| 18 | - | - | - | - | - | - | - | - | 0.58 | 0.72 |
| 19 | - | - | - | - | - | - | - | - | - | - |
| 22 | 0.49 | 0.42 | 0.35 | 0.34 | 0.45 | 0.37 | 0.42 | 0.49 | 0.46 | 0.40 |
| 24 | - | 0.43 | 0.50 | 0.51 | - | 0.45 | - | 0.40 | 0.53 | 0.25 |
| 30 | 0.56 | 0.54 | 0.53 | 0.51 | 0.52 | 0.53 | 0.63 | 0.76 | 0.62 | 0.49 |
| 31 | 0.41 | 0.40 | 0.46 | 0.39 | 0.28 | 0.45 | 0.38 | 0.57 | 0.47 | 0.61 |
| 32 | - | 0.44 | 0.40 | - | - | 0.29 | 0.35 | - | 0.40 | 0.41 |
| 33 | - | - | - | - | - | - | - | - | - | - |
| 34 | 0.52 | 0.50 | 0.46 | 0.57 | 0.50 | 0.48 | 0.63 | 0.66 | 0.70 | 0.69 |
| 35 | - | - | - | - | - | - | - | - | - | - |
| 37 | 0.33 | 0.27 | - | - | - | - | 0.17 | 0.44 | 0.42 | 0.37 |
| 38 | - | - | - | - | - | - | - | - | - | 0.59 |
| 39 | 0.63 | 0.57 | 0.45 | 0.34 | 0.38 | 0.43 | 0.41 | 0.60 | 0.56 | 0.67 |
| 41 | - | - | - | - | - | - | - | - | - | - |
| 42 | 0.25 | 0.44 | 0.51 | - | 0.38 | 0.39 | 0.36 | 0.30 | 0.43 | 0.45 |
| 43 | - | - | - | - | - | - | - | - | - | - |
| 44 | 0.60 | 0.68 | 0.57 | 0.54 | 0.53 | 0.61 | 0.66 | 0.71 | 0.62 | 0.71 |
| 45 | 0.68 | 0.84 | 0.62 | 0.74 | 0.66 | 0.68 | 0.83 | 0.82 | 0.79 | 0.85 |
| 48 | 0.50 | 0.43 | 0.55 | 0.59 | 0.64 | 0.30 | 0.56 | 0.68 | 0.55 | 0.53 |
| 50 | 0.75 | 0.72 | 0.85 | 0.76 | 0.62 | 0.79 | 0.77 | 0.82 | 0.87 | 0.90 |
| 51 | - | - | - | - | - | - | - | - | - | 0.41 |
| 55 | 0.42 | - | 0.82 | 0.75 | 0.73 | 0.70 | 0.79 | 0.65 | 0.89 | 0.87 |
| 60 | 0.39 | 0.50 | 0.66 | 0.52 | 0.59 | 0.55 | 0.68 | 0.63 | 0.58 | 0.69 |
| 63 | - | - | - | - | - | - | - | - | - | - |
| 64 | - | - | - | - | 0.39 | 0.59 | 0.55 | 0.49 | 0.41 | 0.47 |
| 65 | - | - | - | - | - | - | - | - | - | 0.27 |
| 66 | - | - | 0.25 | - | 0.39 | 0.47 | 0.41 | 0.59 | 0.58 | 0.49 |
| 70 | - | - | - | - | - | - | - | - | - | - |
| 71 | 0.71 | 0.70 | 0.63 | 0.60 | 0.50 | 0.61 | 0.69 | 0.66 | 0.68 | 0.61 |
| 72 | 0.61 | 0.83 | 0.59 | 0.67 | 0.71 | 0.64 | 0.71 | 0.68 | 0.73 | 0.67 |
| 73 | - | - | - | - | - | - | - | - | - | - |
| 75 | - | - | - | - | - | - | - | - | - | 0.40 |
| 76 | - | - | - | - | - | - | - | - | - | - |
| 77 | - | - | 0.43 | 0.54 | 0.26 | 0.34 | 0.53 | 0.52 | 0.48 | 0.43 |
| 79 | 0.79 | 0.76 | 0.81 | 0.79 | 0.73 | 0.78 | 0.89 | 0.86 | 0.77 | 0.87 |
| 80 | 0.20 | 0.37 | 0.21 | 0.29 | 0.16 | 0.15 | 0.26 | 0.28 | 0.17 | 0.11 |
| 85 | - | - | 0.32 | - | 0.37 | 0.50 | 0.51 | 0.58 | 0.47 | 0.39 |
| 90 | 0.59 | 0.75 | 0.78 | 0.73 | 0.74 | 0.74 | 0.80 | 0.73 | 0.82 | 0.88 |
| 92 | 0.53 | 0.40 | 0.42 | 0.44 | 0.27 | 0.49 | 0.49 | 0.49 | 0.55 | 0.66 |
| 98 | 0.51 | 0.52 | 0.42 | 0.39 | - | 0.46 | 0.45 | 0.39 | 0.39 | 0.36 |

# Elbow method curve